Since these irregularities are carried by the wind, they prove to be good "tracers" of the mean wind.

The wind profiler transmits short pulses of radio energy in a selected direction and at a selected frequency. Because irregularities exist in the size range from a few centimeters to many meters, the wavelength must also be in the centimeter to many-meter range. Profilers must therefore operate at frequencies considerably below those of the conventional weather radar. The best operating frequencies are in the HF band (3 to 30 MHz), the VHF band (30 to 300 MHz) and the lower end of the UHF band (300 to 3000 MHz). Most of the existing wind profilers operate near either 50 MHz or 400 MHz. All of them can "see through" clouds. Systems operating above 400 MHz are sensitive to rain, which at times may contaminate the wind measurements. Echoes from precipitating hydrometeors are rarely present (except in unusually heavy rain) at the lower frequencies. Therefore wind profilers operating at these lower frequencies (HF and lower VHF) have "all-weather" capability.

Useful echoes can be obtained throughout the troposphere and lower stratosphere. For normal operating conditions, the height range over which useful echoes are obtained is typically between a few hundred meters and 14 to 18 km. A few "super profilers" observe to greater heights and some of the smaller, portable units only measure up to 5 km or less.

The highest altitude from which scattering can be detected depends upon the average power transmitted, the size of the antenna, meteorological conditions, and the frequency (or wavelength) of the transmitted radio wave. The dependence of scattering on the first three of these factors is fairly obvious: the greater the transmitted power or the larger the antenna, the stronger the return signal and the greater the height range of detection. Likewise, the more turbulent the atmosphere, the stronger the returned signal and the greater the height range of detection. The dependence of scattering upon the fourth factor, frequency, is related to the abundance of scatterers of the appropriate size.

The smaller irregularities (cm size) are abundant only at the lower heights. The higher frequency waves, therefore, aren't backscattered as effectively at the greater heights as are those at the lower frequencies (Figure 3). Profilers that operate at the lower frequencies can therefore "see" higher into the atmosphere than those that operate at the higher frequencies.

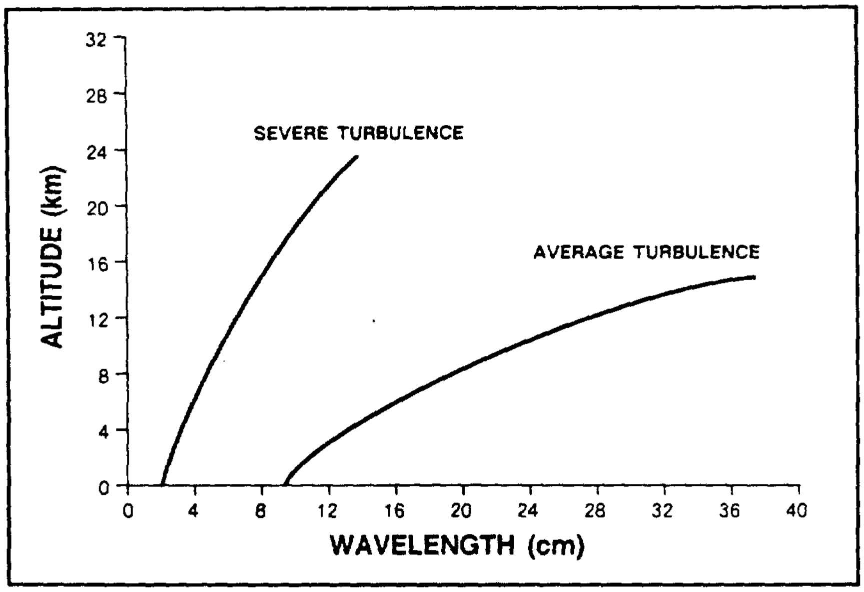

Figure 3 *The maximum altitude from which usable data can be obtained depends upon radar wavelength and the degree of turbulence. (Adapted from Gossard and Strauch, 1983.)*

The lowest height from which useful echoes are obtained depends upon the electronics of the profiler. The receiver is disconnected from the antenna before the transmission of a pulse, to prevent its circuits from being overloaded, and reconnected a short time after the pulse has been transmitted. Because the backscattered energy from the lowest altitudes arrives when the receiver is disconnected, the echoes that originate from the portion of the atmosphere adjacent to the ground are not measured. Pulse length and system recovery time determine the lowest measurable height.

Echoes are received from all heights within the range of operation of the profiler. The received signal is spread out in time, with echoes from the lower heights arriving before those from the greater heights (Figure 4). Echoes from equally-spaced heights are obtained by measuring (sampling) the returned signal at equally-spaced times; this is referred to as range gating. Because the transmitted pulse has a finite length, at any instant the received signal is coming from a volume of the atmosphere (spread of ranges), rather than a single height (single range), as shown in Figure 5. This spread is called the resolution and is equal to one-half the pulse length. Normally, the sampling interval used in range gating is set equal to the resolution to assure that the sample points are independent of each other. Most profilers have a range resolution between 100 and 500 meters.

The transmitted radio energy is not only confined to a certain pulse length, it is also concentrated into a beam. The angular width of

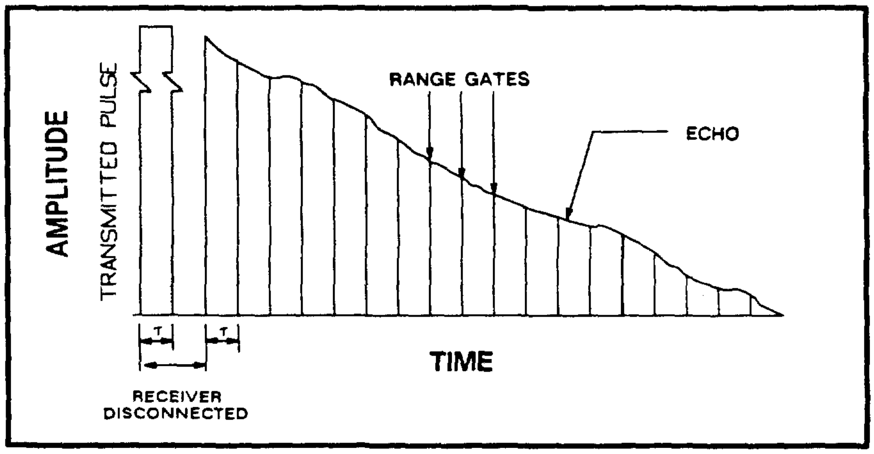

Figure 4 After each pulse is transmitted, the echo is sampled at selected times (range gates).

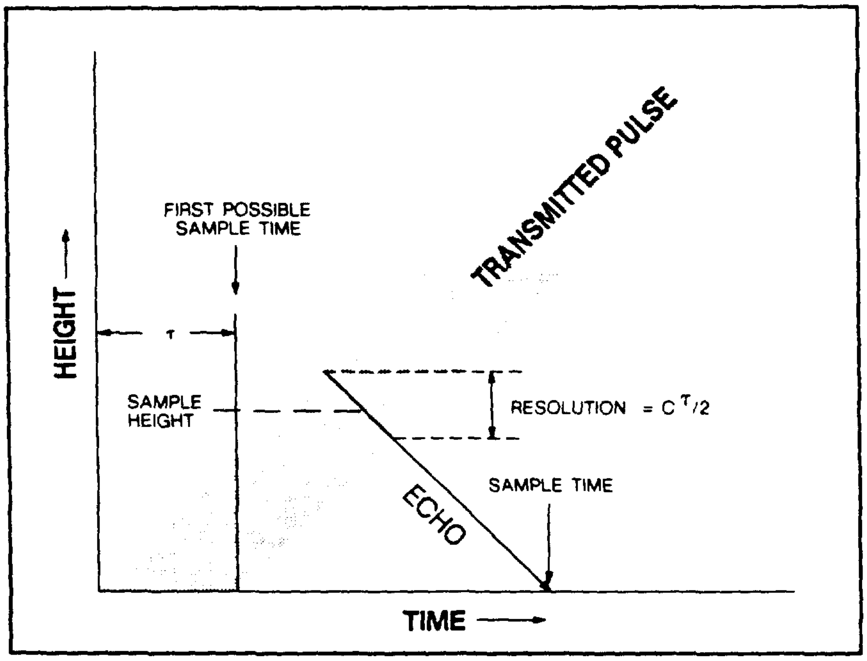

Figure 5 The echo received at any range gate corresponds to a range of heights, called the resolution. This is half the pulse length. The height assigned to that range gate is that of the center of the resolution cell.

the beam depends upon both the effective area of the antenna and the operating frequency of the profiler. Since the beam needs to be narrow, either a large antenna or a relatively high operating frequency is required. For best results, the angular beam width should be 5° or less, although useful results can be obtained with wider beams. For a given beam, the linear width (cross beam) is proportional to the range; for example, at a range of 5 km, 5° corresponds to a width of 436 meters and at 10 km it corresponds to 873 meters. The volume of air that is being sampled at any instant therefore typically measures several hundred meters on a side and contains many eddies.

The wind profiler transmits radio energy within a narrow band of frequencies. If the scattering volume has a component of motion toward or away from the radar, the returned signal will be shifted in frequency by an amount proportional to the speed of this motion. By measuring this frequency shift (the Doppler shift), one can calculate the radial velocity of eddies within the scattering volume and thus of the wind. The radial velocity in one direction is not enough to define the wind vector; measurements in three directions are needed. In the usual configuration, measurements are made using three beams: one tilted to the east, one tilted to the north, and one vertical. In some cases, beams tilted to the west and south are also used. The profiler beams are generally pointed to high elevation angles. The sampling volumes are therefore relatively close to each other and represent the same flow regime. Figure 6 shows the beam configuration for one of Tycho's profilers.

2.4 SIGNAL PROCESSING

In principle, wind velocities of any magnitude, of great accuracy, and from any range could be determined if there were no restrictions on the data. In practice, however, the data are restricted in several ways.

The rate at which pulses are transmitted, the Pulse Repetition Frequency (PRF), limits the range over which heights can be unambiguously determined. (Alternately, one can think in terms of the reciprocal of the PRF: the Pulse Repetition Period - PRP.) If the PRF is too high, the echoes will overlap, that is, echoes will start to be received from one pulse while echoes from the previous pulse are still arriving (Figure 7). Unless some other information is available, it is impossible to interpret these echoes. This is referred to as range aliasing because an echo from a distant scatterer would be attributed to a much closer range gate. The time between pulses must therefore be at least as long as the time delay between transmission of a pulse and reception of an echo from the greatest height expected for useful return.

Velocities (Doppler shifts) can be determined unambiguously only if within certain limits. True Doppler shifts outside these limits

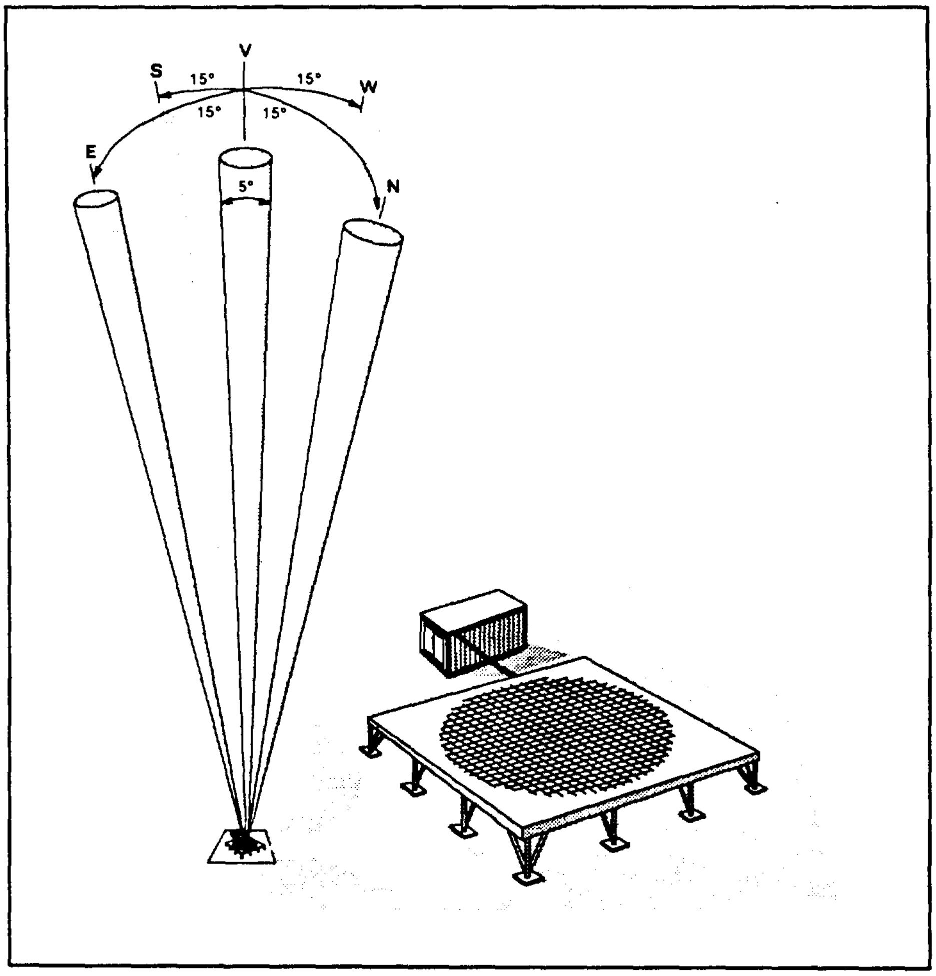

Figure 6 *Typical beam configuration in wind profiling consists of three beams: one vertical, and two tilted 15° from the zenith (to the east and north, for example). Under some circumstances, two additional beams are needed (such as to the south and west).*

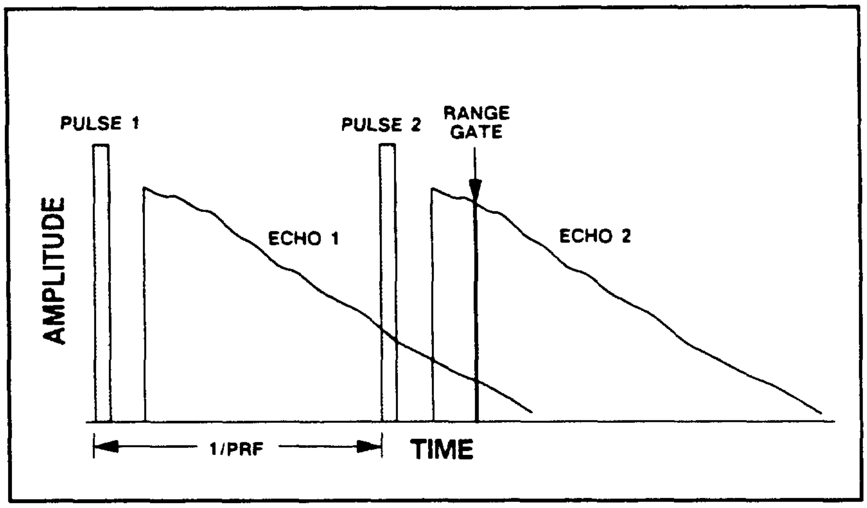

Figure 7 *Example of Pulse Repetition Frequency (PRF) being too large. Echoes are still being received from the first pulse after those from the next pulse start to arrive. The range gate shown by the arrow would contain data from two different heights. This is called range aliasing.*

appear as different frequencies and the deduced velocity is incorrect. This is referred to as velocity aliasing. The frequency limits over which the Doppler shift can be determined unambiguously for any height depend upon the effective sampling rate. When samples are not averaged, the sampling rate is the same as the rate at which pulses are transmitted, the PRF. To maximize the range of radial velocities that can be determined unambiguously, the effective sampling rate should be as large as possible. A compromise between this requirement and that of range aliasing, which requires a PRF as small as possible, must be achieved. In practice, this compromise is easy to reach.

For each range gate, several hundred samples are gathered and then converted into a frequency spectrum using a mathematical inversion technique known as the Discrete Fourier Transform (DFT). Figure 8 is a sketch of such a spectrum. In actual profiler applications, the computer algorithm used to compute the DFT is called a Fast Fourier Transform (FFT). The central frequency corresponds to the transmitted frequency; to the right and left of this are the Doppler shifted frequencies. Positive Doppler shifts correspond to motions toward the profiler and negative shifts to motions away from the profiler. The sketch shows a peak to the right of center, that is, motion toward the profiler. As shown in the sketch, four quantities are measured from each spectrum: the noise power (the amount of background signal) - or equivalently, the average noise level; the signal power returned (the area of the peak above the noise level); the average Doppler shift of the peak; and the width of the peak. The Doppler shift can be converted into the radial velocity component of the wind. The power return and the width of the peak at each range gate are measures of the degree of turbulence in the sampled volume.

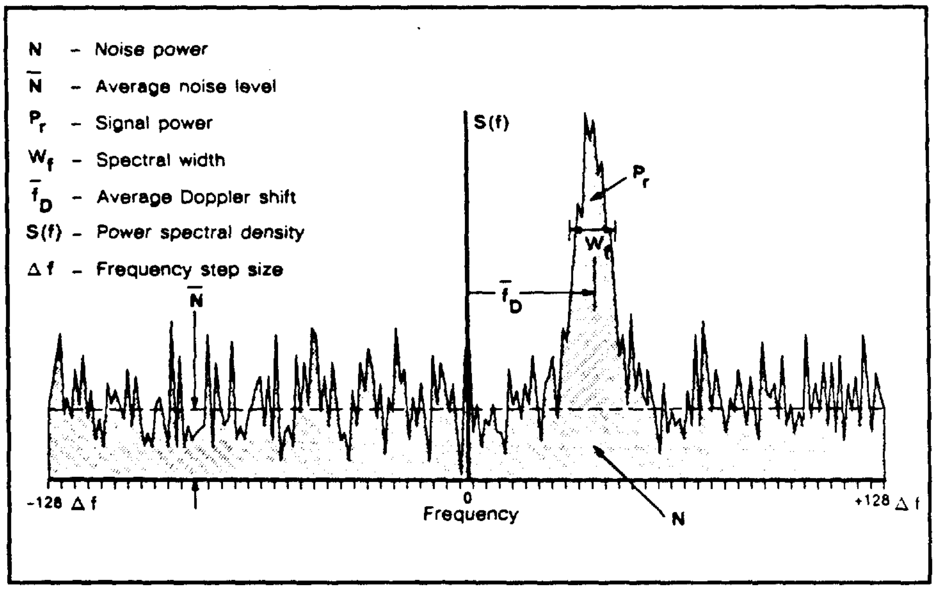

Figure 8 Typical power spectrum showing measurement parameters.

For some range gates, a peak is also seen at the center of the spectrum. This is caused by reflections from solid, stationary targets (such as buildings) in the sidelobes of the antenna pattern. This is called ground clutter. It is removed by mathematical signal processing techniques.

Noise in the spectrum is due to cosmic background radiation (mostly from our own galaxy) and electronic noise in the system. Noise causes uncertainty in the measurements but can be largely compensated for by signal integration techniques. Two types of integration are used for each range gate, those computed in the time and frequency domains. Time domain averaging (integration) consists of taking the mean of several consecutive samples in time before the FFT is computed. Frequency domain, or spectral averaging (integration), consists of calculating a mean spectrum from several consecutive spectra after the FFT computations have been performed. Figure 9 shows the steps commonly involved in reducing the raw data to a Doppler spectrum; both types of averaging are shown. (Some of the steps may be performed in a different order, in some systems.)

Time domain averaging not only reduces noise, it also reduces the computational load of the FFT. A disadvantage, however, is that it limits the range of Doppler shifts (and thus radial velocities) that can be determined unambiguously. The effective sampling rate is the PRF divided by number of samples in the time domain average. The number of samples used in the average depends upon the maximum winds expected.

Spectral averaging makes the peak in the returned signal better defined. This leads to more reliable determinations of power received, Doppler shift, and spectral width. Its disadvantage is that it reduces the time resolution of the final results. If noise were not present, it would take only a few seconds to get reliable spectra. In the presence of noise, however, many spectra must be averaged, giving a time resolution of minutes. One to two minutes per beam is typical.

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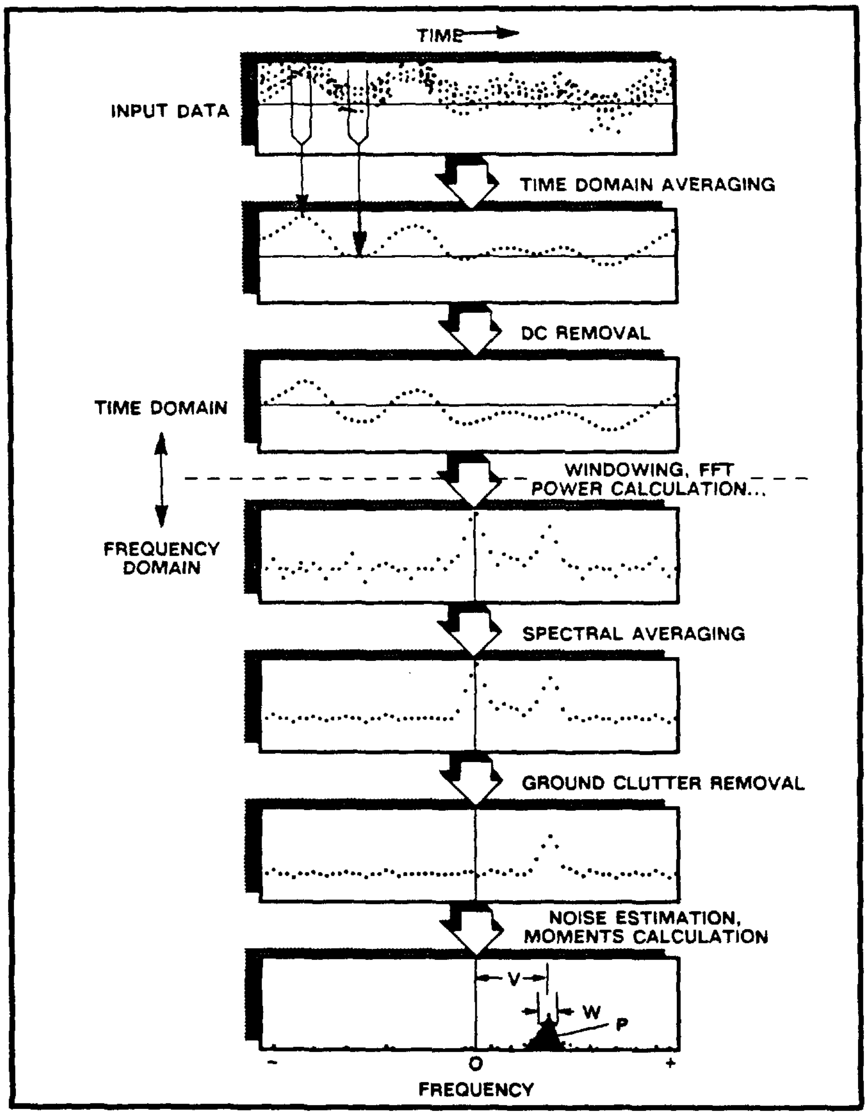

Figure 9 The processing steps normally used in computing the wind and turbulence data. The order of some of the steps may be different in some systems.

Another processing task that is sometimes used in wind profiling is called "windowing". This technique is used to reduce the influence of certain mathematical artifices associated with the FFT.

3. WIND PROFILER DESIGN

3.1 OVERVIEW

A wind profiler consists of a transmitter, antenna, receiver, processor with its firmware, and an enclosure for the electronics. Data communications and display hardware, although not strictly part of the profiler, must also be included to form a complete system.

Figure 10 illustrates the basic operation of a Tycho-engineered wind profiler. On command from the Processor Subsystem, the antenna Controller/Monitor Processor (CMP) sets up the proper phasing for the desired antenna beam position. The transmit/receive (T/R) pulse sets up the T/R switch for transmit mode. (At the higher frequencies, the T/R switch is replaced by a circulator, which automatically routes signals to the proper destination without a prompt from the processor.) The processor sends a prompt signal (pulse) to the receiver/modulator, which produces a pulsed RF signal. This is then amplified by the transmitter and sent to the Antenna Subsystem to complete the transmit cycle. The receiver is disconnected from the antenna during the transmit cycle to prevent overloading it.

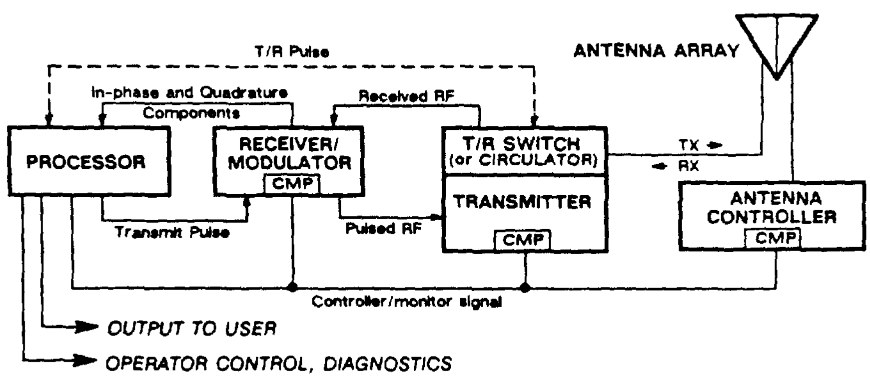

Figure 10 Block diagram of wind profiler radar.

The system is then set to the receive configuration. The receiver is reconnected and the T/R switch (or circulator) directs the weak return signal from the antenna to the Receiver Subsystem. The receiver amplifies the signal and extracts the in-phase and quadrature (or sine and cosine) phase components from which the radial wind velocity is derived. Filtered outputs from the receiver are sent to the Processor Subsystem, which performs the various processing steps necessary to produce the radial wind component and other important parameters relative to the return signals from that beam.

The processor controls the cycles through this sequence for each beam position (north, east, and vertical) to produce the three-dimensional velocity fields. Many wind profilers are also capable of operating as a "five-beam" system (that is, south and west beams as well). A five-beam system can potentially provide better quality data because of additional data consistency checks.

Specific details of hardware will not be given here. Refer to Tycho's specifications sheets for such details.

4. SITE SELECTION AND PREPARATION

A number of practical issues need to be considered when choosing a site and preparing it for the installation of a wind profiler. These issues are much the same for all sizes of profiler, although some obvious differences exist.

The ideal site for a wind profiler is either a shallow valley or a wide, flat area, distant from buildings and mountains, with no ground or air traffic nearby, and a minimum of electromagnetic noise. To aid in the attenuation of sidelobe radiation, it is beneficial (although not necessary) to have trees or other vegetation surrounding the installation at a height somewhat greater than the antenna. Normally, the actual site falls short of these ideal conditions but compromises can be made. For example, air traffic over the site will cause some data to be lost but this is often preferable to choosing a less convenient site.

It is important to check the availability of electricity in the area under consideration. Standard AC power is required for the radar and enclosure (including air conditioning and heating). Transmission line losses must be considered. Proximity to existing electrical service is also an important consideration since lengthy cable connections are often expensive and increase the overall cost of installation.

Tycho's wind profilers are ideal for installation in remote locations. In extremely isolated areas (islands, mountainous terrain, etc.), it may be necessary to arrange delivery via special means (helicopter, boat, etc.). In these locations, power could be supplied by diesel generators that can operate unattended for up to six months. If the radar is to be delivered by truck, then the site should be appropriately accessible. In some cases, it may be necessary to deliver the system in parts using a smaller vehicle. It is also important to consider legal property access rights in cases where the access road passes through the property of a second party.

Once an appropriate location has been chosen, preparing the site for radar installation is a relatively simple procedure. Ideally, the location chosen will be reasonably level. If this is not the case, grading may be necessary. Large rocks, tree stumps, high vegetation, and other protruding objects must be removed from the antenna installation area. Installation costs can be reduced by choosing a site requiring a minimum of leveling and clearing.

Figure 11 illustrates the appearance of a site with an installed wind profiler - in this case, a Model 400. The antenna must be horizontal and, therefore, there are some obvious limitations on the slope of the ground. Clearly, large antennas impose more severe restrictions on ground slope than do small antennas.

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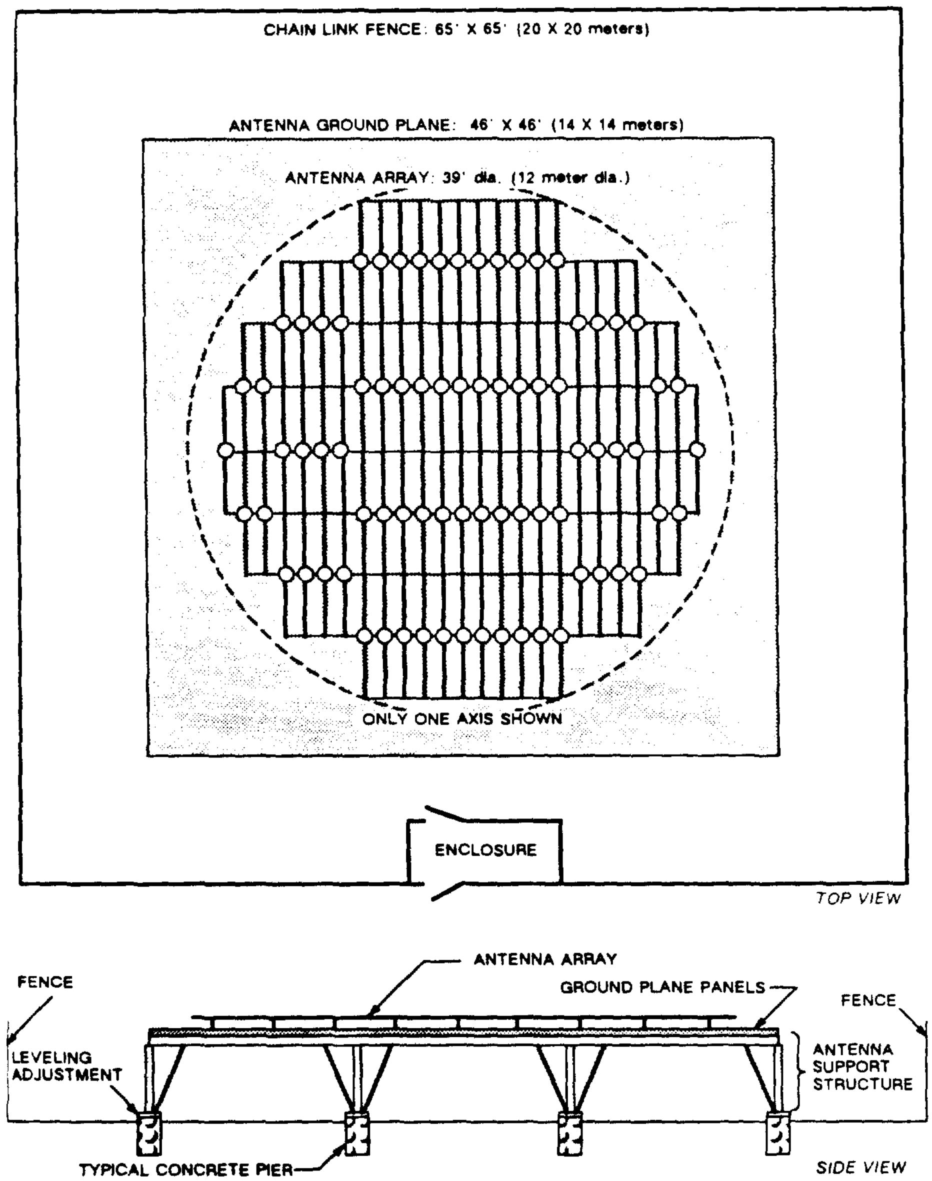

Figure 11 Typical Model 400 wind profiler site.

5. WIND PROFILER DATA

In Tycho's wind profilers, the output of the real-time processor includes wind data in the form of three spectral moments (received signal power, radial velocity, spectral variance) and noise level for each beam, mode, and range gate. Complete spectra can also be output for user-selected range gates, beams, and modes.

The conversion of the spectral moment data to three-dimensional winds and turbulence is normally done in a separate computer, which also is used for data archival, display, communication, and other types of processing. The data can be displayed in a large variety of manners. Two of these are shown below. Figure 12 displays the three wind components and the horizontal wind speed (a combination of the east-west and north-south components) for one time. Figure 13 shows the horizontal wind speed over a period of several hours as a function of height. In this figure "wind barbs" are used to indicate the speed (number of barbs on the wind indicator) and direction (orientation of indicator) for each height. In this figure, time is plotted from right to left as weather systems normally move from west to east at mid-latitudes; this type of display thus approximates a vertical east-west slice through the atmosphere.

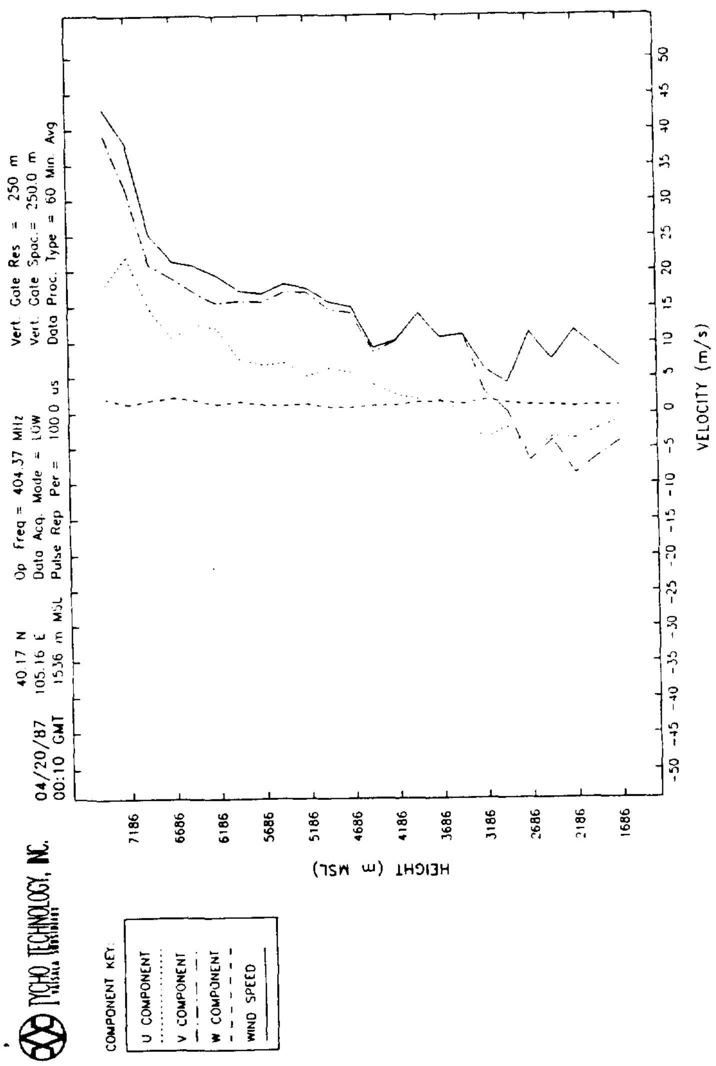

Figure 12 An example of wind data for one six-minute integration. Profiles of the three components (u, v, w) are shown separately. Also shown is the horizontal wind speed, which is calculated from the east-west (u) and north-south (v) components.

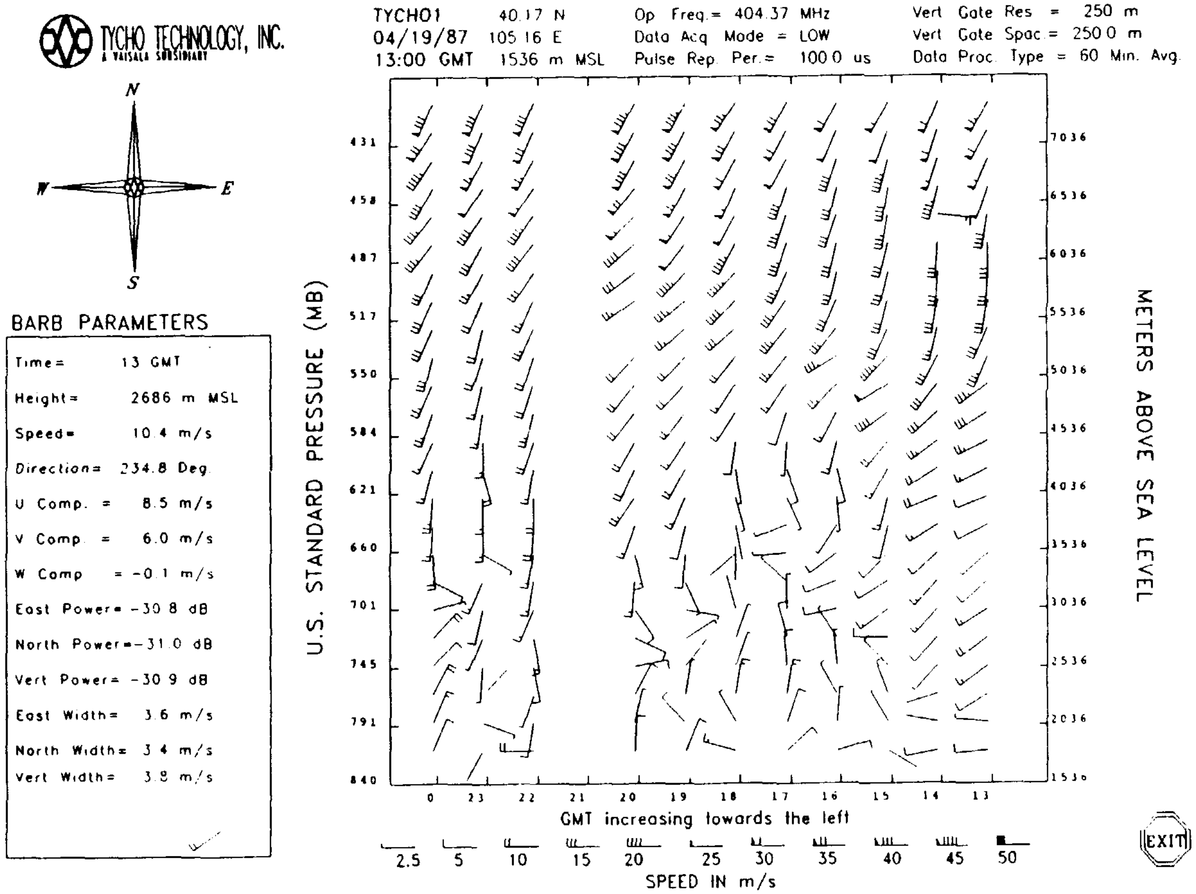

Figure 13 An example of hourly averages of horizontal winds.

APPENDIX A - MATHEMATICAL DETAILS OF WIND PROFILING

Chapter 2 summarized the basic principles behind wind profiling. In this appendix, the mathematical basis of these principles is laid out. Refer to Gossard and Strauch (1983) for a more thorough treatment.

A.1 SOME RADAR BASICS

A.1.1 WAVE MOTION AND THE DOPPLER EFFECT

Figure A-1 illustrates the basic quantities that describe a wave. *Amplitude* is the measure of the magnitude of displacement of a crest or trough from the zero displacement line about which the wave is described. The square of the amplitude is proportional to the energy carried by the wave. *Phase* refers to the position of any selected point along the wave relative to an arbitrarily chosen reference. This reference is normally taken to be the zero crossing point where the slope is positive. Phase is expressed in circular units, with one complete wave corresponding to 360°, or 2π radians. The reference point (zero crossing) is thus 0°, the crest is 90° (or $\pi/2$ radians), and so on. The *wave length* (λ) is the distance between two consecutive points of the same

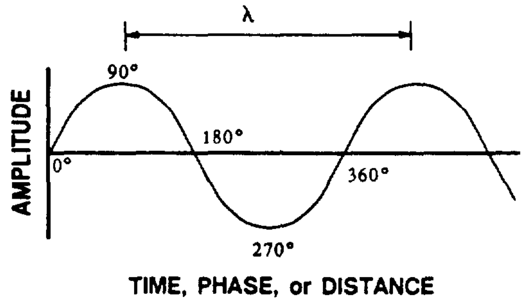

Figure A-1 Wave motion described by amplitude, wavelength (λ), frequency, and phase

phase, such as the wave crests. *Frequency* (f) is the number of wave crests that pass a given point in a unit of time. The unit normally used is cycles/second, or Hertz (Hz). If *c* is the speed of the wave, then wavelength and frequency are related by

$$f \lambda = c \tag{A.1}$$

With regard to wind profilers, the waves are electromagnetic and the medium is the air, in which the speed of the wave is constant and approximately equal to

$$c = 3 \times 10^8 \text{ m/s}$$

Therefore, a frequency of 50 MHz corresponds to a wavelength of 6 meters; 400 MHz corresponds to 75 cm; and so on.

If there is relative motion between the source of the waves and an object encountering the waves, the frequency measured at that object will be different from that at the source. This is called the *Doppler effect*. If the object is approaching the source, the frequency will be higher; if it is receding, the frequency will be lower. The amount of frequency change – called the Doppler *shift* – is directly proportional to the relative radial velocity between the source and the object and inversely proportional to the wavelength. In the case of wind profiling, the source is the wind profiler and the object is the refractive irregularity that scatters the waves. A double Doppler shift is encountered here: one shift as the pulse impinges on the scattering volume and another as the pulse is scattered back toward the wind profiler. The Doppler shift is therefore

$$f_D = -2 V_r/\lambda \; ^{\bullet} \tag{A.2}$$

• Not everyone uses the negative sign in equation (A.2). For example, in the Data Exchange Format, a format used by NOAA for its profiler network, the negative sign is omitted.

where V_r is the radial velocity of the scatterers along the beam. The negative sign arises from the fact that positive radial velocities refer to motion away from the radar, which causes the frequency to be lower. As an example, if the wind profiler is operating at a frequency of 400 MHz (λ = 75 cm) and the radial velocity is −10 m/s, the Doppler shift would be 26.7 Hz. If the operating frequency is 50 MHz (λ = 6 m), the Doppler shift would be 3.33 Hz. These Doppler shifts are only 0.0000066% of the operating frequency − very small indeed! (Incidentally, a 10 m/s radial velocity along a beam tilted 15° from the zenith corresponds to a horizontal wind of nearly 40 m/s!)

A.1.2 ANTENNA BASICS

An antenna may be viewed as the physical interface between air and instrument. The energy delivered to the antenna by the transmitter is radiated into the air in the form of electromagnetic waves. If the antenna were a point source, the energy would radiate equally in all directions. In the case of wind profilers, the antenna usually consists of many radiating elements distributed over a horizontal surface. As the energy radiates from these elements, the waves interfere with each other. In some places, the wave crest from one element will coincide with the crest from another and the waves reinforce. In another place, the crest of one wave may coincide the trough of another, in which case they cancel. By the proper combination of element spacing, power distribution, and phasing, the radiated energy can be concentrated into a selected direction to form a beam. Even though most of the energy is concentrated into a main beam, some minor beams, called sidelobes, are also formed. One of the objectives of antenna design is make the sidelobes as small as possible.

Near the surface of the antenna, the beam is not well defined. This region is called the "near field". At a sufficiently large distance from the antenna, the beam becomes well defined in the sense that rays from the antenna impinging upon some target are essentially parallel. This region is called the "far field". The dividing line between near field and far field is somewhat arbitrary and dependent upon the application. Mathematically, the far field is defined as the range, R, that satisfies the inequality

$$R > c_1 d^2/\lambda \tag{A.3}$$

where d is the maximum linear dimension of the antenna and c_1 is a constant, usually 1 or 2, depending upon the application. Wind profilers normally operate in the far field as echoes from the near field are difficult or impossible to interpret properly. As an example: for a 50 MHz profiler with a 100–meter antenna diameter, $R > 1.67\ km$ if we use $c_1 = 1$. For a 400 MHz profiler with a 12–meter antenna, $R > 192\ m$. Profilers are sometimes operated with the first range gate less than R.

The beam needs to be as narrow as possible. By using a narrow beam, the scatterers are located more accurately. The distribution of the radiated energy over the sky is known as the antenna beam pattern. An example of such a pattern is shown in Figure A–2. *Antenna gain*, G, is defined as the ratio of the actual energy delivered to a given point in space to the theoretical amount that would be delivered if the antenna radiated isotropically – that is, the same in all directions. The direction of maximum gain, G_0, is the direction of the main beam. The width of the beam is usually defined as the angular separation of the half–power points – that is, the points where the gain is $G_0/2$. The larger the value of G_0, the narrower the beam. For wind profiling, a beam width of 5° or less is needed – though, if only the lower reaches of the troposphere are being examined, a somewhat greater beam width can be tolerated. G_0 is directly proportional to the size of the antenna:

$$G_0 = 4\pi A_e/\lambda^2 \tag{A.4}$$

where A_e is the *e*ffective *a*rea of the antenna. A_e is related to the *p*hysical *a*rea, A_p, by

$$A_e = e_a A_p \tag{A.5}$$

where e_a is the antenna efficiency, the value of which depends upon the efficiency of the feed and the antenna illumination. Typical values for e_a are on the order of 2/3.

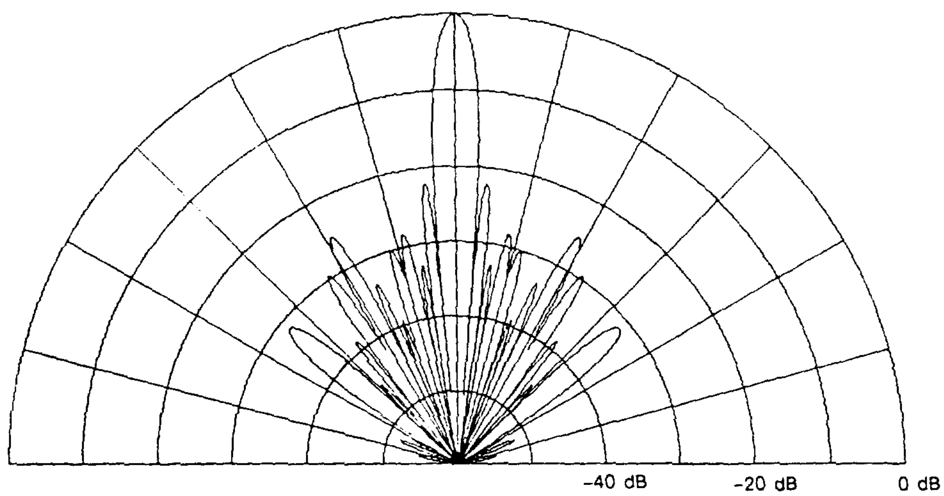

Figure A–2a Computed E-plane antenna pattern of Tycho's Model 400

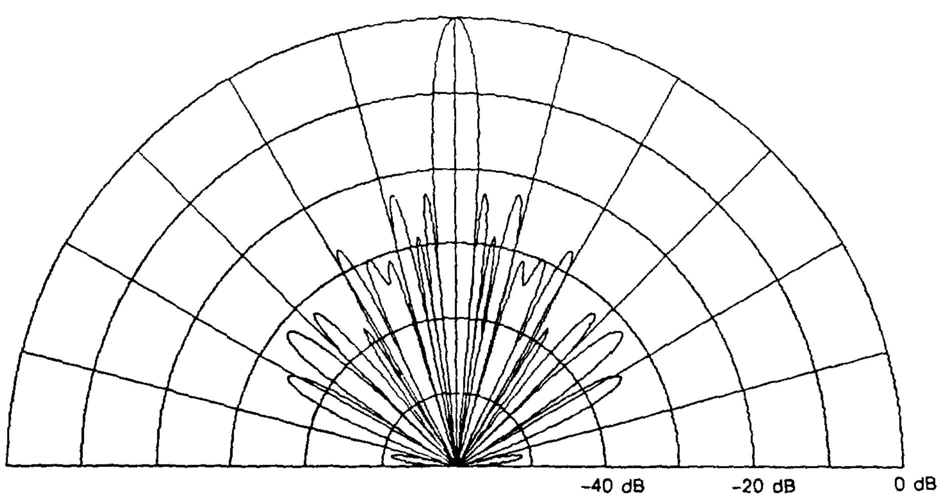

Figure A–2b Computed H-plane antenna pattern of Tycho's Model 400

A parameter similar to gain is directivity, D. D would be the same as G if the antenna efficiency were 100%. Mathematically,

$$G = e_a D \tag{A.6}$$

For a phased array antenna, such as is common in wind profilers, the relation between maximum directivity, D_0, and beam width is approximately

$$D_0 = 32,400/\beta_1\beta_2 \tag{A.7}$$

where β_1 and β_2 are the beam widths (in degrees) in two orthogonal planes passing through the center of the beam. (This approximation is for narrow beams and array-type antennas.) For example: if the beam widths in the two orthogonal directions are each 3°, the maximum directivity would be 3600. This is sometimes expressed in the logarithmic notation of decibels (dB) - in this case, 35.56 dB.

Equations (A.4) through (A.7) show that the larger the antenna or the shorter the wavelength, the narrower the beam produced. If $\beta_1 = \beta_2 = \beta$ and $A_p = \pi(d/2)^2$, where d is the diameter of a circular antenna, then

$$\beta = \frac{180}{\pi}\frac{\lambda}{d} \tag{A.8}$$

For example: to get a 3° beamwidth at 400 MHz, the antenna diameter should be approximately 14 meters. Computer modeling of a specific antenna design is needed for a more accurate estimate.

A.1.3 OPERATIONAL CONSIDERATIONS

Before acquiring a wind profiler, both the principal objective of the system and available operating frequency allocations available to achieve that objective must be considered. Wind profilers normally operate between approximately 40 and 1000 MHz; the most common frequencies used are at approximately 50 and 400 MHz. The advantages of the lower frequencies are that they are less sensitive to precipitation